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MEASUREMENT OF THE AIR-FLOW VELOCITY IN THE CYLINDER OF AN AIRPLANE ENGINE

By Hermann Wenger

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MEASUREMENT OF THE AIR-FLOW VELOCITY IN THE CYLINDER OF AN AIRPLANE ENGINE*

By Hermann Wenger

The investigation of the air flow in the cylinders of reciprocating engines plays a very important part in the design of internal combustion engines. The design of the combustion chamber and arrangement of the intake and exhaust valves have an effect on the turbulence of the air-fuel mixture. Air flows were first investigated by introducing filaments and observing the motion through glass cylinders. The magnitude of the air velocities in externally driven Diesel engines have been measured by Hintz (reference 1) and Geiger (reference 2), who determined the rotational component of the rotating air mass about the vertical cylinder axis. Hintz found the local velocity to fluctuate during the cycle between 0 and 55 meters per second for an engine speed of 200 revolutions per minute. Geiger, in his measurements carried out on a running Diesel engine but mostly without fuel injection, found velocities of from 0 to about 25 meters per second. The velocity was found to increase with increasing engine speed. Geiger found furthermore that the air velocity at the instant of ignition has a decided effect on the quality of the combustion. J. Ulsamer (reference 3) similarly measured the air velocities in his tests on an air compressor. For this purpose he made use of a hot-wire anomometer, which apparatus will also be employed in the present tests. Three speeds were investigated: namely, 63, 128, and 172 revolutions per minute. He found velocities up to 12 meters per second, which occurred during the intake stroke. The mean velocity was likewise found to increase with increasing engine speed.

The object of the present investigation is to determine the velocity in the BMW-VI cylinder of an externally driven single-cylinder test engine at high engine speeds using the hot-wire method of Ulsamer.

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*Messung der Strömungsgeschwindigkeit im Zylinder eines fremdangetriebenen BMW-VI Flugmotors. Luftfahrtforschung, vol. 16, no. 2, Feb. 20, 1939, pp. 62-73.

I. THE TEST SET-UP

a) Method of Measurement with the Hot Wire

A thin metal wire was employed for measuring the air velocity in the cylinder. The method is based on the fact that the cooling of an electrically heated wire by the air increases with increasing velocity of the latter. To each air velocity there will correspond a definite wire temperature. Since the dimensions of the wire can, within certain limits, be kept very small, the measurements will be practically free from inertia lag. With different arrangement and length of the wire mean values may also be determined for various measuring cross sections.

1. Principles of Velocity Measurement with the Hot Wire

In tests carried out at the heat engine laboratory at the Munich Technical High School, J. Ulsamer measured the air-flow velocities in the cylinder of an air compressor. The general principles of his method will be described briefly here.

An electrically heated metal wire is situated in an air stream. In the condition of equilibrium, the electrical energy supplied to the wire must be equal to that transferred to the air from the surface of the wire. Any periodical variation in the air stream must naturally be followed by a variation in the heat transferred from the wire surface to the air and hence also in the electrical energy supplied to the wire, provided that the wire dimensions are sufficiently small for it to follow the periodic changes with practically no inertia lag. Denoting the heat energy in heat units supplied to the wire in unit time by U and the heat yielded in the same time interval to the air stream by Q, then in the equilibrium state the following equation must be satisfied:

$$U = Q \tag{1}$$

The supplied energy U is given by

$$U = 0.86\ i^2\ r \tag{2}$$

where i is the current in amperes through the measuring wire

and r, the resistance in ohms.

Now the resistance of the wire depends on its temperature, according to the following relation:

$$r = \varphi(T_w) \tag{3}$$

where T_w is the absolute temperature. Equation (2) therefore becomes

$$U = 0.86\ \psi(i^2,\ T_w) \tag{4}$$

The wire is heated by the supplied energy, U. The variable velocity results in a change in the wire temperature and hence in the wire resistance. The latter is measured by comparison with a precision resistance and the current by means of an oscillograph loop.

The heat transmitted to the air stream (reference 4), neglecting small flow velocities, is given by the following equation:

$$\frac{\alpha\ d}{\lambda_m} = f\left[\frac{d\ \rho_m\ w}{\eta_m}\right] \tag{5}$$

In order to evaluate the above relation, there is required a knowledge of the temperature of the surrounding air. The latter is also measured with the hot wire, which is now employed as a resistance thermometer.

In equation (5):

- d is the diameter of the wire (m);
- α, the mean heat-transfer coefficient for the entire wire surface (kcal/m² h °C.);
- λ_m, the heat conductivity of the medium (kcal/mh °C.);
- η_m, the viscosity coefficient of the medium (kgs/m²);
- ρ_m, the density of the medium (kgs²/m⁴);
- w, the velocity of the medium at some distance from the wire surface (m/s).

If T_w is the absolute temperature of the wire surface and T_0 the absolute temperature of the surrounding medium at some distance from the wire, the mean values in equation (5) are defined as follows:

$$\lambda_m = \frac{1}{T_w - T_o} \int_{T_o}^{T_w} \lambda \, dt \tag{6}$$

$$\eta_m = \frac{1}{T_w - T_o} \int_{T_o}^{T_w} \eta \, dt \tag{7}$$

$$\rho_m = \frac{1}{g} \frac{1}{T_w - T_o} \int_{T_o}^{T_w} \gamma \, dt$$

$$= \frac{1}{g} \gamma_o \frac{T_o}{T_m} \tag{8}$$

where γ_o (kg/m^3) is the specific weight of the medium at temperature T_o,

$$T_m = \frac{T_w - T_o}{\ln \frac{T_w}{T_o}} \tag{9}$$

and g (m/s^2) is the acceleration of gravity.

The function f must be determined experimentally. There are a number of tests available on the heat transfer of thin wires. On the basis of the results of these tests, the function f is found to be:

$$\frac{\alpha\ d}{\lambda_m} = m \left[\frac{d\ \rho_m\ w}{\eta_m}\right]^n = m(Re)^n \tag{10}$$

The values of the coefficient m and the exponents n are given according to J. Ulsamer in the table below:

	Re	n	m
For	$0.1 < Re < 4$	0.305	0.875
	$4 < Re < 50$	.41	.764
	$50 < Re$ to 1,000	.5	.537

2. The Effect of the Humidity and the Direction of the Air Flow on the Heat Transfer from Thin Wires

It was shown by J. Ulsamer (reference 3) that the effect of the air humidity on the heat transfer from thin wires may be neglected, the error that arises from the neglect amounting to about ±2 percent, which lies within the limits of accuracy required of the function f.

In setting up the function f, the case was assumed where the wire is situated at right angles to the flow direction. It was found by J. Ulsamer (reference 3) that the heat transfer is lowered considerably with reduction in the angle α. For a ratio of the length to diameter of the wire equal to 400, the heat transfer with the wire parallel to the flow direction is three-fourths of the value for the wire at right angles. The transverse position is thus characterized by the maximum power absorption. In the present investigation, a still more favorable length to diameter ratio equal to 1,300 was employed.

3. Objects of the Measurements

According to Newton's law, the heat transmitted to the air stream is given by

$$Q = \alpha\ F\ (T_w - T_o)(\text{kcal/h}) \tag{11}$$

where $F = \pi\ d\ l\ \ (m^2)$ and

$$\alpha = \frac{\lambda_m}{d}\ m\ Re^n$$

Transforming equation (11) by means of equations (5), (6), (7), and (8), there is obtained

$$Q = \Phi\,(T_w,\ T_o,\ P_o,\ w) \tag{12}$$

We have furthermore equation (4):

$$U = 0.86\,\psi\,(i^2,\ T_w) \tag{4}$$

For a condition of equilibrium, the electrical energy supplied U in each time interval must be equal to that conducted away Q:

$$0.86\ \psi(i^2,\ T_w) = \Phi(T_w,\ T_o,\ P_o,\ w) \tag{13}$$

From the above equation the velocity w of the air stream may be computed by determining the following magnitudes:

1. i, the current in amperes through the hot wire;
2. T_w, the absolute temperature of the hot wire;
3. T_o, the absolute temperature of the surrounding air in the cylinder;
4. P_o, the air pressure in the cylinder (kg/m²).

The above relations hold accurate for the cooling of a hot wire in a steady air stream. They may also be applied to a periodically varying air flow because the thickness of the boundary layer at the wire is very small.

b) The Electrical Measuring Circuit

The measuring wire is used both as a resistance thermometer and as a hot wire. As a thermometer, it serves for the measurement of the air temperature and as a hot wire, for the determination of the velocity. For the latter purpose, the resistance of the thin wire must be reliably determined by the electrical measuring circuit. In applying the wire as resistance thermometer, the wire must be very lightly loaded in order not to increase the value of the resistance by the Joule heating of the wire and thus measure too high a temperature. For measuring the air temperature in the cylinder, the wire is connected in the current circuit I (fig. 1). The wire in series with a sensitive oscillograph loop (Siemens and Halske, type V) is put across a voltage divider. The magnitude of the required voltage may readily be determined from the following relation:

$$E = (r_{loop} + r_{wire})(\max I_{loop}) \tag{14}$$

where r_{loop} is the resistance of the loop;

r_{wire}, the smallest value of the resistance of the wire;

max. I_{loop}, the largest permissible current in the loop.

The resistance itself is determined by comparison with a precision resistance of the firm, Hartmann & Braun.

When used as a hot wire for measuring the velocity, it is connected to circuit II (fig. 1). Here the wire is put in series with an oscillograph loop and a precision ammeter and connected to a battery of 4 volts. In order to keep the voltage of the battery of circuit II as constant as possible, the storage battery is provided with a resistance during the entire test period. Here again the resistance is determined by comparison with a precision resistance and the current with the aid of the precision ammeter.

The oscillogram is obtained in the following manner. First, the resistance box is connected to the circuit I. By inserting the proper values of the resistance, lines of constant resistance, and therefore lines of constant temperature are obtained on the recording paper. The resistance box is then disconnected and the wire element switched in. The resistance of the wire varies with the temperature of the surrounding air in the cylinder according to the relation

$$r = \varphi(T_w) \tag{3}$$

Additional heat is received by the wire by the measuring current. Also, investigation was made to determine how high the measuring current may be before the change in heat resistance is practically zero. This was found to be the case for a current of 10 mA. The current used was half this value; that is, a maximum of 5 mA.

In obtaining the hot-wire curves, the wire must be strongly loaded, since it must receive a higher temperature than that of the surrounding air in the cylinder. For this purpose, it was connected to circuit II. Through the changes in the air velocity in the cylinder, the rate of cooling of the wire varies. This results in a change in the wire temperature or its resistance and also the power absorbed. The calibration is the same as with circuit I. There are again obtained calibration lines of constant resistance and also of constant current, the current through the resistance being measured with the precision ammeter. The voltage can therefore also be obtained, being given by Ohm's law:

$$E = i\ r\ (V) \tag{15}$$

The power supplied to the wire is given by

$$U = 0.86\ i^2\ r(\mathrm{kcal/h}) \tag{2}$$

The voltage on the wire changes within certain limits as a result of the voltage drop in the instrument and lead resistances. With the wire placed transverse to the air flow, the cooling of the wire is strongest, the resistance thus the lowest and the current the strongest. The voltage drop will therefore also be the maximum. If care is taken, however, to see that the latter is small compared to the wire voltage, as may be done by keeping the instrument and lead resistances small, then the heat conducted to the air stream, which heat is equal to the electrical energy supplied, is a maximum when the current through the wire is a maximum. The transverse air-flow case is thus characterized not only by the maximum current in the wire, but also by the maximum power absorption of the latter. If the ratio of the wire resistance to the instrument and conducting lead resistances were equal to about 1 or less, then the power need not increase with increasing current but will even decrease. In the present case, the most unfavorable ratio was about 8.

Figure 2 shows the oscillogram curves for the wire used as thermometer and hot wire. For the temperature curves about 10 cycles were photographed above one another. For the hot-wire curves, it is necessary, in order to obtain the maximum speeds for each piston position, to rotate the wire at right angles to the air flow. If the flow curves are therefore obtained for different positions of the hot wire in the cylinder, the envelope of the family of curves at each position gives the maximum velocities as a function of the crank angle. The hot-wire curves are also taken for nine spindle settings (from 20° to 20°) for about 10 cycles. This gives altogether about 90 cycles. The curves for any definite spindle setting do not cover each other but give a scattered band which practically coincides with the bands of the other eight spindle settings. The direction of the velocity vector during the individual cycles cannot be determined on account of the strong scattering of the curves at a definite spindle setting.

c) The Measuring Instrument

1. Construction of the Measuring Instrument

The wire element employed for the measurements is

.006"

shown in figure 3. A thin tungsten filament of 15 μ diameter is stretched between the fork-shaped bent supports of 1 mm constantan wire which at the same time serve as current leads. The supporting wires must be made much stronger in order to withstand the increased mechanical stresses at the high-speed engine. It is not possible furthermore, to connect potential leads of the same thin tungsten wire since the thin wires could not be soldered hard or electrically welded. The wire was attached to the supports in the following manner. A fine slit was first notched in the 1 mm constantan wires and then filled with silver solder. The wire below this slit was then heated until the solder attained the melting point. At this instant, the hair wire was introduced into the slit and the flame removed. The wire was then clamped by the contracting silver solder. This method of attachment was found to be very good. It was first tried with soldering tin. On account of the continuous tensile stressing of the wire by the strong air current, however, the wire was gradually drawn out from the soft tin.

The insulated supporting wires were led through the spindle c and cemented into the forward part of the latter. The remaining portion of the instrument was the same as employed by J. Ulsamer. Only for attachment to the cylinder the sleeve a was differently designed. Figure 3 shows the entire measuring instrument. The wire element d is situated within the cylinder. At e, the supporting wires are fastened to the spindle c. The supporting wire is then led through the spindle outward to the clamps n. With the aid of the screw i, the spindle can be displaced axially in the sleeve b. The graduation on i gives a measure of the displacement and the zero position can be determined by a mark on the ring k. The sleeve b is situated in another sleeve a in which by loosening the cap screw f it may be rotated. The setting is read off on the graduations on the disk g. The pointer h marks the zero position which corresponds to a fixed position of the wire to the vertical. The rotating motion of sleeve b is positively transmitted by the screw l to the spindle c. The measuring wire in this manner receives two degrees of freedom: it may be rotated about the instrument axis and be displaced in the direction of the latter. The sleeve a is then attached in another sleeve A (fig. 7), which is screwed into the cylinder by means of the flange.

2. Simplifications Introduced in the Design of the Instrument

On account of the finite thickness of the wire, the measurements will not be entirely inertia-free and the temperature of the wire surface will be different from the temperature of the wire axis. Furthermore, the wire temperature will not be able entirely to follow the air temperatures in the cylinder. In what follows, it will be shown with the aid of the work by H. Pfrien (reference 5) how great an error in the most unfavorable case is to be expected from measurements with a tungsten wire of 15 μ diameter.

For the ratio of the amplitudes of the harmonically varying air temperature to the wire temperature, H. Pfriem obtains the following relation:

$$\frac{\vartheta_o}{t_o} = \sqrt{(1 + \sigma_o)^2 + (\omega\ z_o)^2} \qquad (16)$$

where ϑ_o is the amplitude of the gas temperature (°C.);

t_o, the amplitude of the wire temperature at the surface (°C.);

ω, the cyclic frequency of the temperature fluctuation (1/h);

σ_o, the heat fraction radiated;

z_o, the time lag of the wire (h)

given by

$$z_o = \frac{r_o\ c_o\ \gamma_o}{2\ \alpha_o} \qquad (17)$$

From the above equation it may be seen that the lag z_o becomes smaller when the heat transfer coefficient α_o becomes larger. For the case under consideration

r_o (wire diameter) = 7.5×10^{-6} m,

c_o (specific heat) = 0.034 kcal/kg °C.,

γ_o (specific weight) = 19,200 kg/m³,

λ_o = 138 kcal/m h °C.,

α_o (the heat-transfer coefficient).

In his investigations, H. Pfriem employed wires of 0.1 mm diameter and found for the smallest heat-transfer coefficient a value of about 800 kcal/m² h° C. and a maximum value of about 5,000 kcal/m² h° C. For a wire of diameter of 0.15 mm, using the relation

$$\frac{\alpha_1}{\alpha_2} = \left[\frac{r_1}{r_2}\right]^{n-1} \quad (n = 0.5) \quad \text{(most unfavorable value)} \qquad (18)$$

there are obtained heat-transfer coefficients of about 2,000 and 12,500 kcal/m² h °C., respectively. The value of z_o is then $z_o = 1.224 \times 10^{-6}$ h (α_o = 2,000 kcal/m² h °C).

Figure 4 shows the ratio of the amplitudes ϑ_o/t_o, neglecting σ as a function of the engine speed with the heat transfer coefficient α_o as parameter. The middle curve shows the error that occurs at $\alpha_o = 4{,}000$. For this case, there is obtained at a speed $n = 2{,}000$ rpm a maximum error of about 2.7 percent.

For the phase displacement ϵ of the amplitudes of the wire temperature with respect to that of the harmonically varying gas temperature, there is obtained the following expression:

$$\epsilon = \operatorname{arc\,tan} \frac{\omega\, z_o}{1 + \sigma_o} \qquad (19)$$

On neglecting the radiation ($\sigma_o = 0$), there is then obtained

$$\tan \epsilon = \omega\, z_o \qquad (20)$$

The values of ϵ are plotted in figure 5 against the engine speed with the heat-transfer coefficient α_o as parameter

In our measurements, the following phase displacements and corresponding heat-transfer coefficients were determined:

n (rpm)	α (kcal/m² h °C.)	ϵ^o
500	2,000	5
1,000	2,800	8
1,500	3,600	11
1,800	3,900	12

The values of α given in the above table are the lowest that occur in the complete cycle. On drawing a horizontal in figure 5 through the point $n = 1,800$ and $\alpha_0 = 4,000$, it may be seen, when the line is transferred on figure 4, that the error can never exceed the value of 2.3 percent, since the values in the above table all lie below this line. The error must therefore be correspondingly smaller and may be directly taken from the figure.

It will now be shown that the temperature of the wire axis follows the temperature of the surface with an error of less than 1 percent. This will be true if

$$\frac{\omega\, r_o^2}{4\ \alpha_o} \ll 1 \qquad (21)$$

For our case, there is obtained for the above expression the value $0.000025 \ll 1$. The entire wire therefore heats up practically simultaneously.

It is further necessary to compute the error due to the heat conduction at the points of attachment of the wire. For this purpose, H. Pfriem in his paper also set up a relation:

$$t_m = 1/l_o \int_o^{l_o} t_x\ dx = t_o \left[1 - \frac{\tanh(\nu\, l_o)}{\nu\, l_o}\right] e^{j\omega\tau} \qquad (22)$$

For the values of $l_o \sqrt{2\ \alpha_o/r_o\ \lambda_o} \geqq 3$, the value of $\tanh(\nu\, l_o)$ equals 1 with an error of less than one-half percent, and we thus obtain

$$t_m = t_o \left[1 - \frac{1}{\nu\, l_o}\right] e^{j\omega\tau} \qquad (23)$$

where l_o (m) is half the wire length and

$$\nu = \sqrt{\frac{2\ \alpha_o}{r_o\ \lambda_o} \sqrt{1 + (\omega\, z_o)^2}} \quad (1/m) \qquad (24)$$

In figure 6, the expression $(1 - 1/\nu\, l_o)$ is plotted as a function of the rotational speed with the heat transfer coefficient α_o as a parameter. The error is here practically independent of the speed and in the most favorable case amounts to about 3 percent.

In deriving the above relation, the temperature of the point of attachment was taken as the origin of the temperature scale. Actually, however, the temperature of the supports lies much higher. It was further assumed that the material of the supports was the same as that of the measuring wire. In our case, however, constantan was employed, a material which has a very small heat-conduction coefficient. The values of $(1 - 1/\nu\, l_0)$ plotted in figure 6 are therefore under all conditions the most unfavorable. Actually the values are far more favorable, so that at a value of $\alpha_0 = 4{,}000$, the maximum error may be considered to be about 2 percent. Adding the error due to the inertia of the measuring wire, an error reading of at most 5 percent may be expected.

While the temperatures are recorded too small by this amount, the power determined from the curves is too large. The power supplied is determined by equation (2):

$$U = 0.86\ i^2\ r (\mathrm{kcal/h}) \tag{2}$$

This is mostly transferred to the surrounding air flow. A small portion is conducted away from the thin measuring wire to the constantan supports. The magnitude of this heat quantity is given by

$$Q_a = \lambda_0 \frac{\Delta t}{\Delta x}\, 2\, F \tag{25}$$

where

$\dfrac{\Delta t}{\Delta x}$ (°C/m) is the temperature drop along the wire at the points of attachment;

F (m^2) the cross section of the measuring wire;

λ_0 (kcal/m h °C.) the heat conductivity of the measuring wire.

Assuming that the error through this heat conduction over the points of attachment is to amount to at most 1 percent of the energy supplied, then from equations (2) and (25) the necessary required temperature drop may be determined:

$$\frac{\Delta t}{\Delta x} = \frac{Q_a}{\lambda_0\, 2\, F} \doteq \frac{0.01 \times 0.86\ i^2\ r}{\lambda_0\, 2\, F} \tag{26}$$

The maximum power supplied to the wire in our tests is 0.8 kcal/h. There is thus obtained a temperature gradient of

$$\frac{\Delta t}{\Delta x} = 515{,}000^\circ \text{ C/m} = 515^\circ \text{ C/mm}$$

The maximum occuring difference in temperature is about 300°. The temperature drop along the wire is assumed to be as shown in diagram B. The correct temperature is then obtained, taking into account the error of 5 percent, as $320 \times \frac{1}{0.95} = 336^\circ$ C. The temperature difference is then 316° and the temperature drop $\frac{\Delta t}{\Delta x} = 316^\circ$ C./mm.

It may be seen that the error of the power measurement is below 1 percent.

In evaluating the measurements, the errors discussed in this section were not taken into account, since the error in the end result (the magnitude of the air velocity) in the most unfavorable case is no greater than the sum of the individual errors, which amounts to about 7 percent. This is all the more justified because the magnitude of the air velocity for several cycles at a definite point of the cylinder fluctuates by a multiple of 7 percent.

II. THE TESTS

1. The Test Set-Up

A single-cylinder DVL test set-up, which enables the investigation of various types of cylinder construction, was employed. A BMW-VI cylinder with a diameter of 160 mm (6.3 in.) and a stroke of 190 mm (7.5 in.) was investigated. The test engine was externally driven by an electric motor whose speed could be varied between 400 and 1900 revolutions per minute. The compression ratio could be varied by the raising or lowering of the cylinder support through a worm gear in the crank case. The measurements were carried out in the compression chamber of the cylinder. Figure 7 shows the cylinder with the mounting of the measuring-instrument apparatus.

A Universal oscillograph of Siemens & Halske was employed for taking the temperature and hot-wire curves. The sprocket was directly coupled to the king shaft of the test engine. For this purpose the spur wheel on the drive shaft of the sprocket had to be removed from the gear of the oscillograph. This had the advantage that the observation arrangement could be employed independently of the photographing arrangement. It was furthermore possible to vary the exposure of the shutter. Normally the shutter opens with the "instant exposure setting" for a revolution of the sprocket. Now, however, it was possible to adjust the rotational speed of the electric motor of the oscillograph and hence the exposure time so that the shutter would be open for any number of working cycles of the test engine. The curves on the screen could now be better observed since they did not appear so strongly drawn out.

For indicating, a DVL glow-lamp indicator was employed. (reference 6). In order to utilize fully the paper width of 9 centimeters for a pressure range of 0 to 9 atmospheres, the lever arm at the deflecting mirror was increased. The rotational speed was measured by means of the DVL counter stopping every two minutes. Since the counter was coupled to the control shaft, the speed of the crank shaft was obtained.

2. Calibration of the Measuring Wire

Before soldering in the wire, the resistance of the leads measured from the double-throw switch was determined. and found to be 0.85 ohm. After attaching the wire, the variation of its resistance with temperature was determined with oil thermostats. For this purpose, the length of the piece of wire was measured under a microscope with sevenfold magnification. The wire was then aged sufficiently so that the resistance remained constant at the same temperature. The resistance in the oil thermostat was then determined in the temperature range from 20° to 300° C. The dependence of the resistance on the temperatue was found to be linear:

$$r = r_0(1 + 0.00354\ t) \qquad (27)$$

This value of the temperature coefficient could be employed, in case one wire were broken, for the next measuring wire if obtained from the same stock as the other. It was only necessary to determine each time the resistance per unit length at room temperature. This value varied for various wire pieces within narrow limits, even if taken from the same stock. The resistance per meter of the thin tungsten wire of 0.15-millimeter diameter at room temperature was about 430 ohms. The length of the measuring wire fluctuated between 19 and 21 millimeters.

From the above data, the resistance of a definite length of the wire could be plotted against the temperature.

3. The Carrying-Out of the Tests

The tests were conducted for the following engine speeds: $n = 500$, 1,000, 1,500, and 1,800 revolutions per minute. The carburetor setting G was varied each time, the setting being 25, 50, and 75. At $G = 75$, the throttle of the carburetor was completely opened. The cross section was about 15 cm^2. The settings $G = 50$ and 25, corresponded to cross sections of 10 and 5 cm^2. At the carburetor setting 0 (closed carburetor, idling engine) no measurements could be taken because the wire always broke after a very short time. The jacket-water temperature $t_k = 13^\circ$ C. and the compression ratio $\epsilon = 4.8:1$ were in these tests held constant. In the measurements with $n = 1,800$ rpm, $G = 25$, 50, and 75, $\epsilon = 4.8$, the jacket-water temperature was increased to $t_k = 75^\circ$ C. In the further measurements $n = 1,800$ rpm, $G = 25$, 50, and 75, $t_k = 13^\circ$ C., the compression ratio was increased to $\epsilon = 5.8$.

The measuring positions in the cylinder are shown in figure 7, these being, for the compression ratio $\epsilon = 4.8$, at 20, 40, 60, 80, 100, and 120 millimeters from the wall and for $\epsilon = 5.8$ at 40, 60, 80, 100, and 120 millimeters from the cylinder wall.

There were first obtained the calibration curves for the air temperature in the cylinder. This was done by connecting the precision resistance box of Hartmann & Braun. By inserting proper values of the resistance, in our case from 8 to 17 ohms, which correspond, according to the relation $r = \varphi(T)$, to definite temperatures, it was possible to draw lines of constant temperature. The measuring wire was now connected in. The latter follows the temperature changes of the surrounding air and thus varies its resistance. As a result, there is a change in the current which flows through it. The current is photographed with the aid of an oscillograph loop. In order to obtain a mean value over several cycles, more than ten cycles were photographed. These curves in general cover each other well. Only at high engine speeds does small scattering occur which, however, extends only over the expansion stroke and shows up in a slight widening of the photograph line. In recording the air temperature curves, it is not necessary that the wire be at right angles to the air flow. On rotating the measuring wire, practically no difference was found in the photograph.

In recording the hot-wire (velocity) curves, however, it is necessary to rotate the wire because the relation according to which the velocity is evaluated holds only for the position of the wire transverse to the air stream. For this reason, the measuring wire was rotated from 20° to 20° about its transverse axis, giving nine positions in the cylinder. For each position curves were obtained for over 10 cycles. Since, as previously mentioned, the transverse air flow is characterized by maximum power absorption, it is necessary to use the envelope for the evaluation. After recording these hot-wire curves, lines of constant resistance (or temperature) are again obtained with the aid of the resistance box. Simultaneously, the current flowing through the resistance is measured, being required for the determination of the electrical energy supplied.

By the foregoing measurements, there are therefore determined:

T_o, the absolute temperature of the surrounding air;

T_w, the wire temperature;

q, (kcal/m h) the electrical energy supplied to the measuring wire per unit length per hour.

The last magnitude still to be determined, namely: the pressure in the cylinder, is obtained from the indicator diagram of the DVL glow-lamp indicator.

The measurements were carried out at the points indicated in figure 7. In figure 8, the air velocity, at a speed of $n = 500$ rpm carburetor setting, $G = 75$, compression ratio $\epsilon = 4.8$ and jacket-water temperature $t_k = 13.5°$ C. is plotted as a function of the crank angle for the measuring positions 1 to 6. For measuring position 4, six curves were recorded; position 2, four curves; and positions 1, 3, 5, and 6, one curve each. The scattering of the curves at each position is so great that a band is obtained for each measuring position, which band practically coincides with the scattering bands of the other positions. It is thus not possible to make out any dependence of the air velocity on the distance of the measuring position from the cylinder wall.

In the succeeding measurements, no separate evaluation was therefore made for the various positions, a procedure which would be very time-consuming. Two photographs were taken for each of the six positions in the cylinder. From the twelve diagrams thus obtained, the values of T_0, T_w, i, and r were measured and the mean values found which were then employed as a basis for the determination of the air velocities. The mean values of the air velocities thus obtained agree, to within the slide rule accuracy, with the mean values which were obtained for a separate evaluation for each measuring position.

4. Analysis of the Test Results

The magnitudes measured in the preceding section were used in evaluating the test results. According to equation (2), $q = 0.86\ i^2\ r$ is the heat in kcal supplied per hour per unit length by the wire to the surrounding air. With the aid of equation (11), the value of Nu is found to be

$$Nu = \frac{\alpha\ d}{\lambda_m} = \frac{1}{\pi}\ \frac{q}{\lambda_m\ \theta_w} \tag{28}$$

With the aid of the gas equation and equation (8)

$$Re = \frac{d\ \rho_m\ w}{\eta_m} = \frac{d}{g\ R} = \frac{P}{\eta_m\ T_m}\ w$$

or

$$\frac{Re}{w} = \frac{d\ P}{g\ R\ \eta_m\ T_m} = y \tag{29}$$

Furthermore, according to equation (10)

$$Nu = m(Re)^n$$

The final equation for the determination of the velocity is therefore obtained as

$$w = \frac{1}{y}\left[\frac{Nu}{m}\right]^{1/n} \qquad (30)$$

To compute the values of Nu and Re/w from equations (28) and (29), there are still required the mean heat-transfer coefficient and the viscosity of the air. These mean values are defined in equations (6) and (7). The heat-transfer coefficient, according to Nusselt, is

$$\lambda = \frac{0.00167\ (1 + 0.000194\ T)\sqrt{T}}{1 + \frac{117}{T}} \quad (\text{kcal/m h}^\circ\ \text{C.})$$

The viscosity of the air, according to Sutherland (reference 7):

$$\eta = 1.69 \times 10^{-6}\ \frac{1 + 117/273}{1 + 117/T}\sqrt{\frac{T}{273}} \quad (\text{kgs/m}^2)$$

For both magnitudes, W. Nusselt gave the integrals between 0 and T from T = 100 to 2,200° K.

III. TEST RESULTS

1. Maximum Air Velocity as a Function of the Crank Angle

The test results are all plotted in figures 9-14. Figure 9 shows the maximum air velocity plotted against the crank angle for the speed $n = 500$ rpm, with the carburetor settings 25, 50, and 75, compression ratio $\epsilon = 4.8$ and jacket-water temperature $t_k = 11^\circ$ C. Figure 10 shows the same curves for $n = 1,000$ rpm; figure 11 for $n = 1,500$ rpm; and figure 12 for $n = 1,800$ rpm. In figure 13, the maximum air velocity is plotted against the crank angle for $n = 1,800$ rpm, $\epsilon = 4.8$; $t_k = 75$ and the carburetor settings 25, 50, and 75. Figure 14 shows the same curves for $n = 1,800$ rpm, $\epsilon = 5.8$, $t_k = 13^\circ$ C. and carburetor settings, 25, 50, and 75.

The maximum velocities occur during the suction period as is also to be expected. With decreasing carburetor setting, the maximum of the curves shifts toward the bottom dead center (180° crank angle). The same phenomenon occurs with increasing engine speed. At the higher speeds and small carburetor settings, the velocities during the exhaust period attain the same values as during the suction period.

Similar measurements were made by J. Geiger (refercence 2) on a 4-stroke-cycle Diesel engine at the speeds n = 250 and 300 rpm. He made use of the dynamic-pressure method already applied by Hintz (reference 1) and Sass (reference 8). With this measuring procedure, only the rotational component of the swirl about the cylinder axis can be determined. Geiger investigated principally the effect on the swirl of a shrouded intake valve. Measurements of the air velocities were carried out also without the shroud. Plotting the velocities found by Geiger against the crank angle, there is found in general a similar variation of the air velocities as obtained in our present investigation.

2. The Mean Air Velocities for the Separate Strokes and for the Complete Cycle as Functions of the Engine Speed

For a more accurate determination of the dependence of the velocity on the engine speed, average values were formed for the separate strokes and for the complete cycle. These are defined as the heights of the rectangles whose areas are the same as those under the velocity curves with the same base length. These values are collected in table I and are plotted in figures 20-22 as functions of the engine speed for the carburetor settings 25, 50, and 75.

The mean air velocity increases with the engine speed or with the mean piston velocity. The increase remains in general always below the increase in the mean piston speed. The maximum velocities always occur during the intake stroke.

3. The Mean Air Velocities for the Separate Strokes and for the Complete Cycle as Functions of the Throttle Setting for Constant Engine Speed

In figures 15-19, the mean air velocity for the various strokes and the complete cycle is plotted against the throttle setting at constant engine speed. The compression ratio $\epsilon = 4.8$ and the jacket water temperature $t_k = 13^\circ$ C. were held constant. In the same figures are also plotted the air velocities for an engine speed of 1,800 revolutions per minute, varying first the jacket-water temperature t_k from 13° C. to 75° C. and then the compression ratio ϵ from 4.8 to 5.8. On increasing the jacket-water temperature, the velocities are decreased by from 10 to 15 percent. The increase in the compression ratio leads in general to an increase in the velocities by about 10 percent. This is due to the greater suction during the intake stroke. During the other strokes, the velocities are also increased as a result of the greater kinetic energy of the air masses entering the cylinder. Generally the increase or decrease in the mean velocities remains within narrow limits.

4. The Test Results of J. Ulsamer.

J. Ulsamer (reference 3) has measured the flow velocities in the cylinder of a slow-running air compressor at speeds of 63, 128, and 172 revolutions per minute. Figures 23 and 24 show the air velocity plotted against the crank angle. The velocity curves have the same general character as found in the present work. J. Ulsamer also finds the air velocity attaining its maximum value during the intake stroke, and decreasing during the remaining strokes of the cycle. In order to bring out more clearly the effect of the engine speed on the gas velocity, J. Ulsamer formed the mean values of the air velocities for the separate strokes as well as for the complete cycle. These are plotted in figures 25 and 26. The mean air velocities increase with the engine speed and are approximately equal to from five to seven times the mean piston velocity. Taking the corresponding values for the measuring positions 7.5 and 70 millimeters from the cylinder wall from figures 24 and 25, forming the mean values over the intake and compression strokes and plotting in figure 21 the values obtained by Ulsamer appear as continuations of our curves for the intake and compression strokes. Ulsamer, however, finds the velocity increasing at a greater rate than linear with the engine speed, whereas we find the contrary to be the case. The mean values for the entire cycle cannot be included since too high values are obtained. This is due to the different mode of operation of the two engines. In the case of the compressor employed by J. Ulsamer, there is one intake stroke for each revolution, whereas in our case, there was one intake stroke for each two revolutions. Since, however, the maximum values of the velocity occur during the intake stroke, the mean value over two strokes must be greater than over four strokes. The mean values over the complete cycle are not therefore comparable.

IV. SUMMARY

The air velocity in the cylinder of a water-cooled BMW-VI airplane engine was measured by means of a hot-wire anemometer. With this apparatus, measurements are possible also where there is a rapidly varying air velocity and air temperature. The mean velocity of the air over the wire length for various positions of the wire element in the cylinder was measured, utilizing an oscillograph loop connected to a potential source. The effect of the engine speed, the throttle setting, the jacket water temperature, and the compression ratio on the air velocity in an externally driven BMW-VI cylinder was investigated. The variation of the air velocity over the cycle in all photographs showsthe same character. The motion attained its maximum velocity during the intake stroke, decreased during the compression stroke and increased again during the expansion and exhaust strokes. The effect of the engine speed and the throttle setting was brought out by plotting the mean air velocities over the separate strokes and over the complete cycle.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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TABLE I

n	500	500	500	1,000	1,000	1,000
ϵ	4.8:1	4.8:1	4.8:1	4.8:1	4.8:1	4.8:1
t_k	11.5	11.0	11.0	13.5	13.5	11.0
G	25	50	75	25	50	75
	w_m	w_m	w_m	w_m	w_m	w_m
Intake	16.97	14.27	11.42	19.19	20.83	22.89
Compression	14.71	8.75	6.50	16.42	14.44	15.61
Expansion	8.31	6.46	5.63	13.94	10.62	13.66
Exhaust	9.97	7.20	6.31	14.61	10.02	10.49
Cycle	12.75	9.50	7.83	16.27	14.35	15.90
n	1,500	1,500	1,500	1,800	1,800	1,800
ϵ	4.8:1	4.8:1	4.8:1	4.8:1	4.8:1	4.8:1
t_k	13.5	13.5	12.0	14.0	14.0	14.0
G	25	50	75	25	50	75
	w_m	w_m	w_m	w_m	w_m	w_m
Intake	21.36	25.80	30.13	23.26	29.23	31.67
Compression	19.76	18.50	19.13	17.77	20.84	22.29
Expansion	17.82	15.60	16.52	17.82	18.28	19.02
Exhaust	21.60	16.12	11.53	21.81	19.67	15.44
Cycle	20.50	19.52	19.70	20.80	22.65	22.47
n	1,800	1,800	1,800	1,800	1,800	1,800
ϵ	4.8:1	4.8:1	4.8:1	5.8:1	5.8:1	5.8:1
t_k	75.0	75.0	75.0	13.5	13.5	13.5
G	25	50	75	25	50	75
	w_m	w_m	w_m	w_m	w_m	w_m
Intake	21.78	26.06	26.22	26.06	29.76	29.44
Compression	17.32	17.05	19.31	21.11	19.31	18.05
Expansion	17.62	16.15	16.80	24.46	16.98	19.75
Exhaust	18.99	15.39	12.99	24.42	20.92	18.00
Cycle	19.25	19.20	19.02	24.33	22.70	21.93

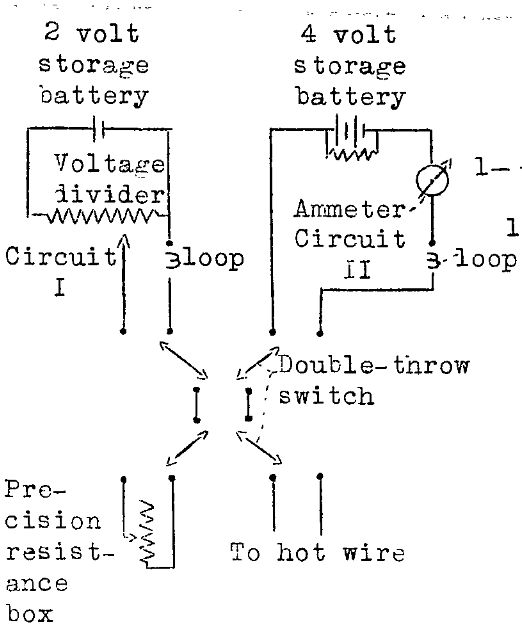


Figure 1.- Scheme of connections of electrical measuring curcuit.

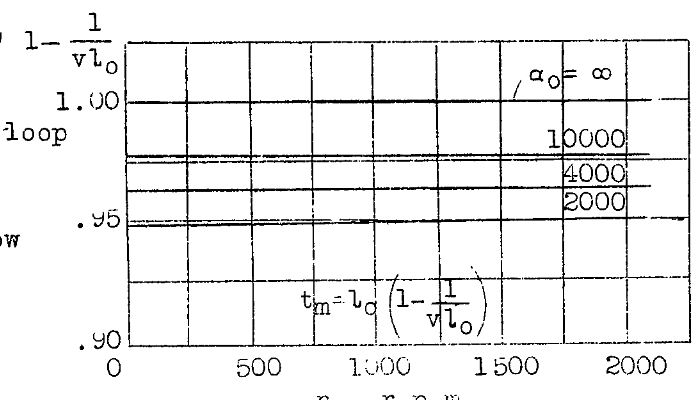


Figure 6.- $(1-1/vl_o)$ plotted against the engine speed

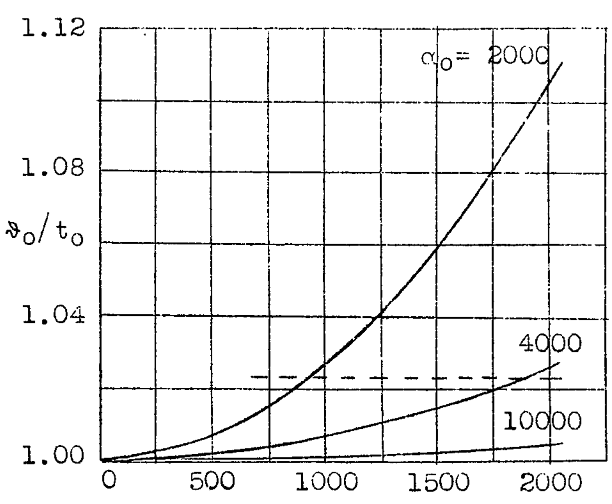


Figure 4.- Ratio of the temperature amplitudes as a function of the engine speed.

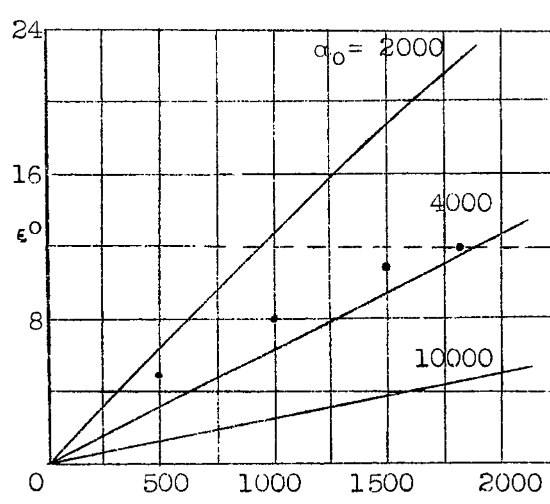
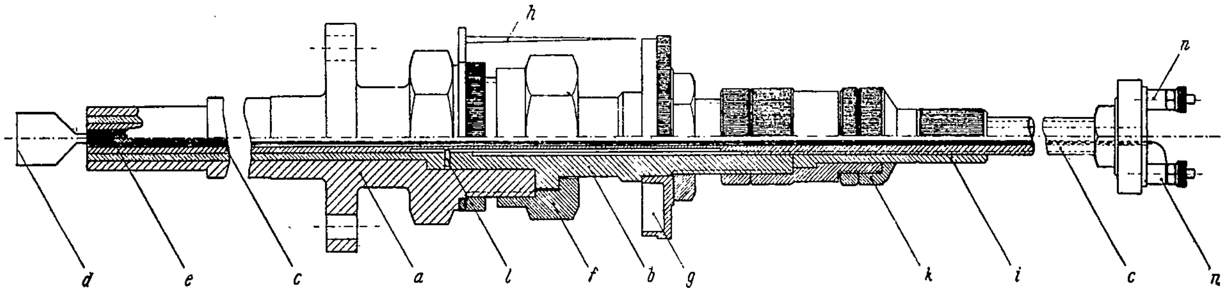


Figure 5.- Phase displacement of the amplitudes of the wire temperature as a function of the engine speed.



a, sleeve.
b, sleeve.
c, spindle.
d, wire element
e, cementing position.
f, nut.
g, disk.
h, indicator.
i, nut.
k, ring.
l, screw.
n, clamps.

Figure 3.- Measuring apparatus.

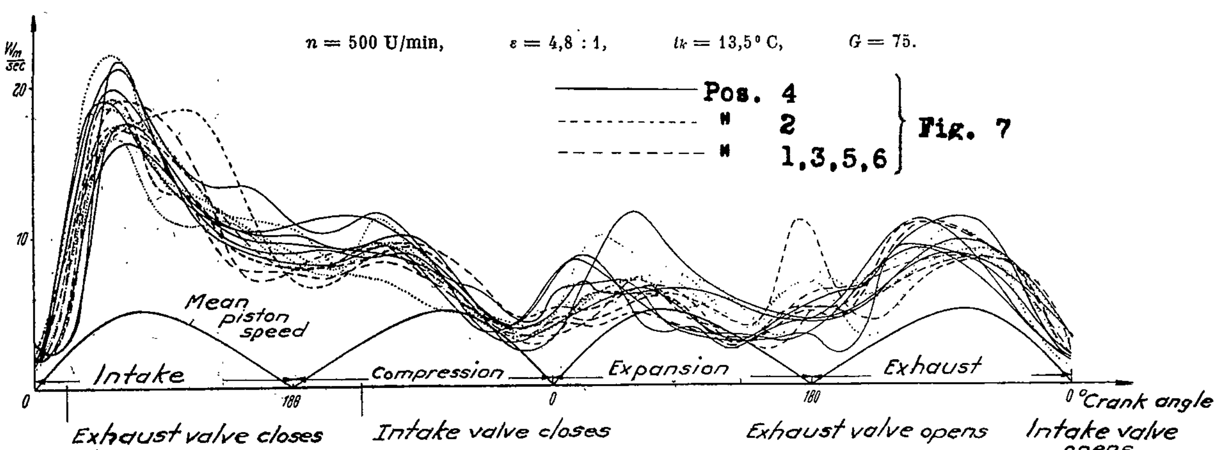


Figure 8.- Air velocity as a function of the crank angle for the six measuring positions.

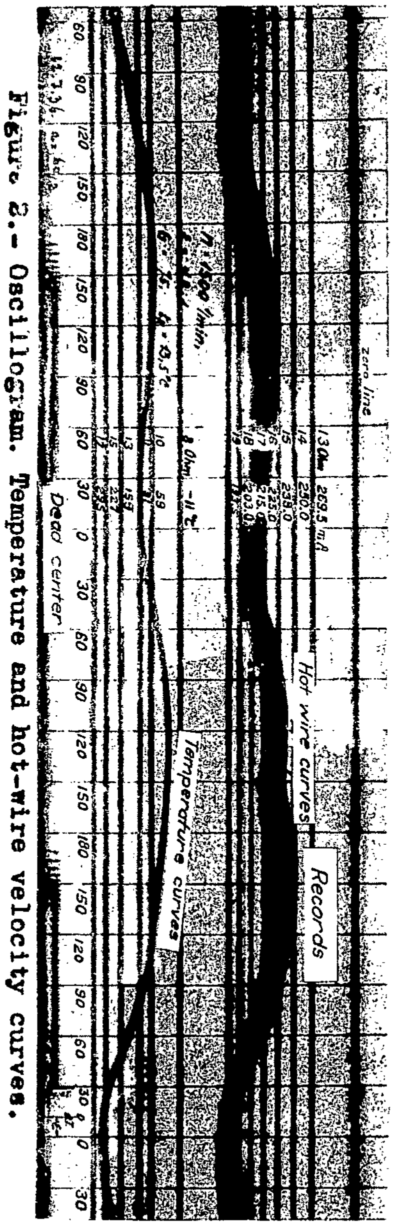


Figure 2.- Oscillogram. Temperature and hot-wire velocity curves.

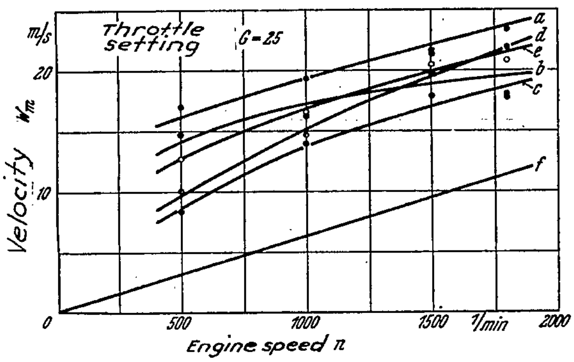


Figure 20.

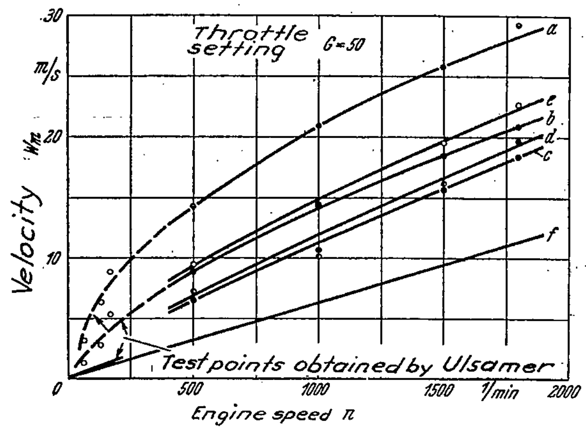


Figure 21.

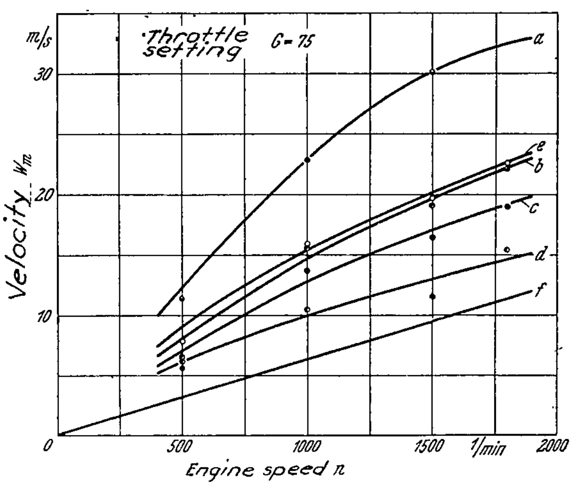


Figure 22.

a, suction. b, compression.
c, expansion. d, exhaust.
e, cycle. f, mean piston speed.

Figures 20 to 22.- Mean values of the air velocities over the separate strokes and over the complete cycle as a function of the engine speed. Compression $\epsilon = 4.8$, jacket water temperature $t_k = 13^\circ C$.

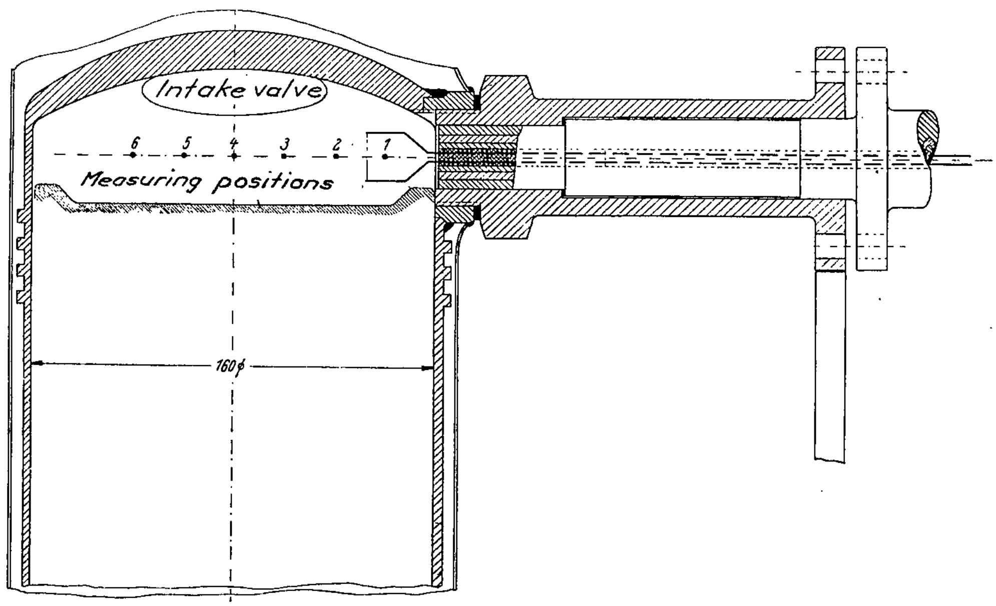


Figure 7.- Mounting of the measuring apparatus.

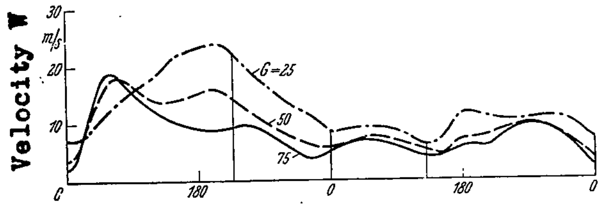


Figure 9. Crank angle,deg.

Speed n = 500 r.p.m.
Compression ratio ϵ = 4.8:1
Jacket water temp. t_k = 11°C
Throttle setting G = 25,50,75

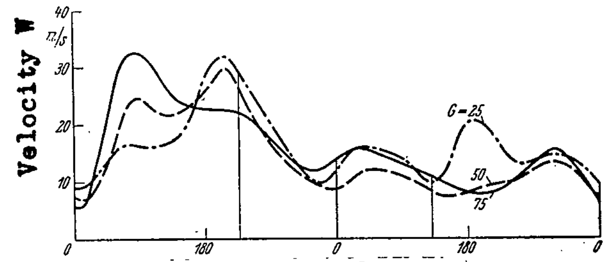


Figure 10. Crank angle,deg.

n = 1000 r.p.m. t_k = 13°C
ϵ = 4.8:1 G 25,50,75

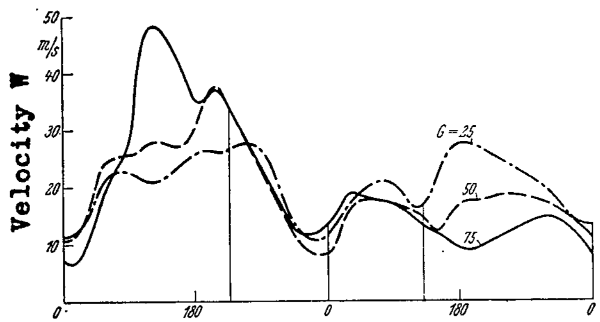


Figure 11. Crank angle,deg.

n = 1500 r.p.m. t_k = 13.5°C
ϵ = 4.8:1 G = 25,50,75

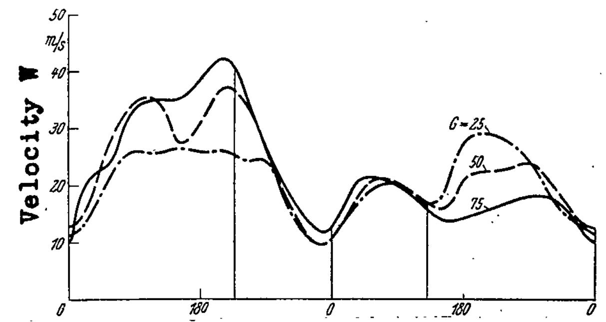


Figure 12. Crank angle,deg.

n = 1800 r.p.m. t_k = 14°
ϵ = 4.8:1 G = 25,50,75

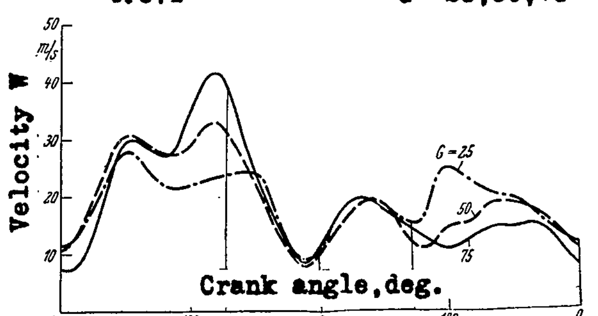


Figure 13. n = 1800 r.p.m. t_k = 75°
ϵ = 4.8:1 G = 25,50,75

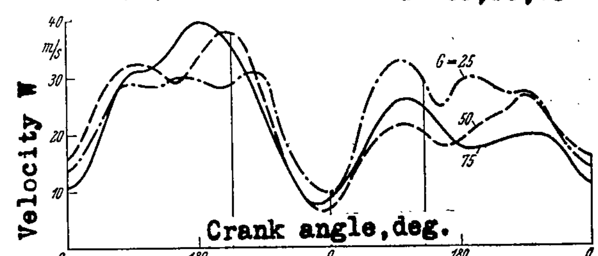


Figure 14. n = 1800 r.p.m. t_k = 13.5°C
ϵ = 5.8:1 G = 25,50,75

Figures 9 to 14.- Maximum air velocity as function of the crank angle.

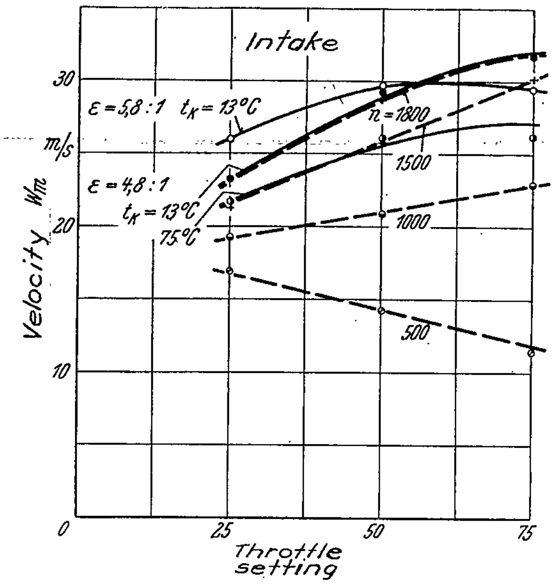


Figure 15.

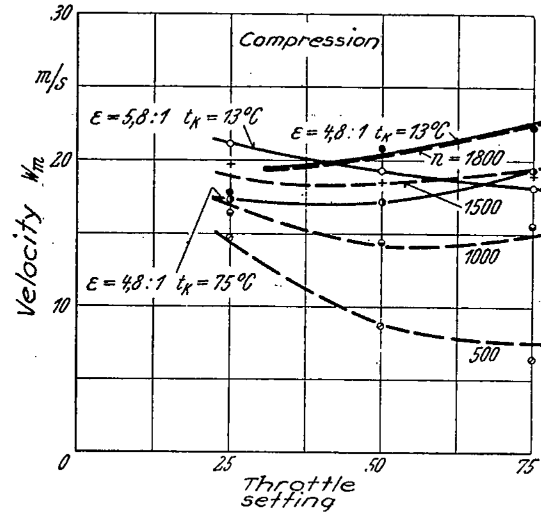


Figure 16.

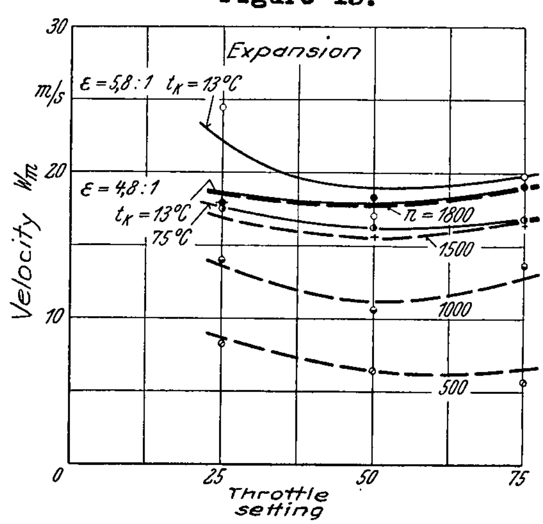


Figure 17.

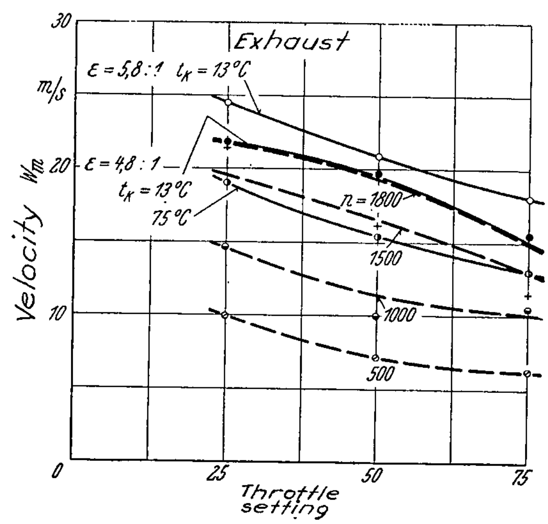
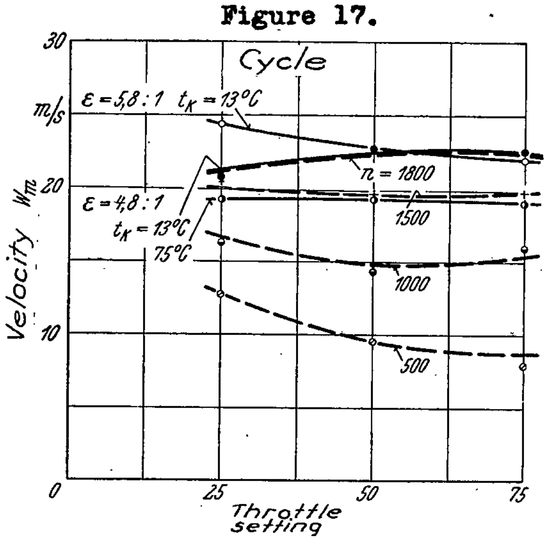


Figure 18.



- - - - - - - - { Compression ratio $\epsilon = 4.8:1$
Jacket water temp. $t_k = 13°C$
———————— Speed n = 1800 r.p.m.

Figures 15 to 19.- Dependence of the mean air velocities over the separate strokes and over the complete cycle on the throttle setting for constant engine speed.

Figure 19.

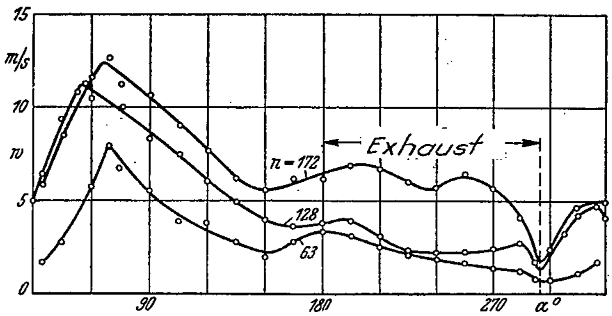


Fig.23-Distance from cover wall 7,5 mm.

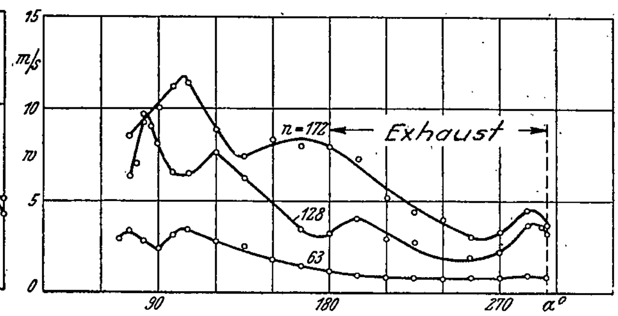


Fig.24-Distance from cover wall 70 mm.

Figure 23,24.- Variation of the air velocity in the cylinder of a slow running air compressor with crank angle for 63128 and 172 r.p.m.

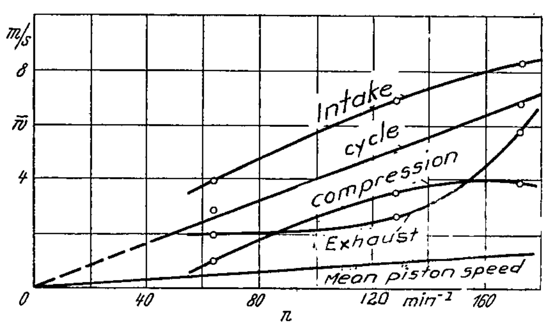


Fig.25-Distance from cover wall 7,5 mm.

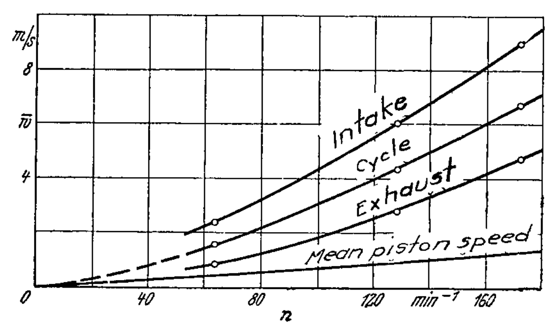


Fig.26-Distance from cover wall 70 mm

Figure 25,26.- Mean values of the air velocities over the separate strokes and over the complete cycle.

Direction of flow

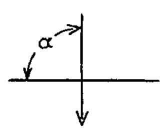


Diagram A

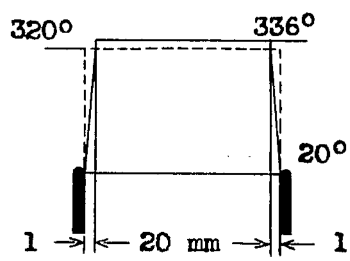


Diagram B